~~On~~ Assessing the ~~intensity~~ Intensification and ~~destructive potential~~ Impact of a ~~past extreme, synoptic storm~~ Historical Storm in a ~~future warmer climate~~Warmer Climate

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Abstract. ~~The global climate is undergoing significant changes, with rising greenhouse gas concentrations driving increased temperatures, altered precipitation patterns, and sea level rise. Yet, the full implications for~~

Extratropical windstorms pose a major hazard in Northern Europe, with damage primarily arising from the combined effects of high sustained near-surface winds and extreme gusts. While future changes in mid-latitude ~~storm systems remain an area of active investigation. This studyexamines how such storms may intensify under future warming, focusing on~~ storms are expected under climate warming, the implications for wind-related impacts remain uncertain. In this study, we investigate the response ~~of thermodynamic warming to an intense historical storm using~~ Storm Anatol, which severely ~~impacted~~ affected Denmark on 3 December ~~1999. Using the high-resolution~~ 1999, as a representative case.

The storm is simulated using the convection-permitting numerical weather prediction model HARMONIE-AROME ~~and~~ within a pseudo-global warming ~~(PGW) framework, the storm is simulated under a range of thermodynamic conditions representative of a warmer climate.~~

~~Results show a clear warming signal, with increased near-surface temperatures and atmospheric moisture contributing to stronger storm dynamics. Wind and gust speeds rise systematically with temperature, while the spatial extent and duration~~ framework. Uniform temperature perturbations are applied throughout the atmosphere, sea surface, and skin layers, while specific humidity is adjusted to maintain relative humidity. Changes in wind speed, gusts, and the spatial and temporal extent of damaging wind conditions ~~also expand~~are analysed across a range of warming scenarios. To quantify ~~these changes, we introduce~~ integrated wind exposure, we employ a new cumulative metric applicable to both wind speed and gust diagnostics, referred to as the Cumulative Wind Exposure Index~~(CWEI), which captures the integrated spatial and temporal severity of wind exposure..~~

~~Application of CWEI reveals a marked increase in~~ The simulations show a systematic intensification of near-surface wind and gust speeds with increasing temperature, accompanied by an expansion in the spatial footprint and duration of extreme wind conditions. The cumulative wind exposure ~~in~~ increases markedly in the warmer scenarios relative to the historical ~~case.~~

~~When linked to established wind-damage relationships, this translates to substantially higher potential for structural damage~~
~~and disruption. These findings suggest that storms like Anatol, already destructive in the past, are likely to become even more~~
~~damaging under future climate conditions. This underscores the need for climate-resilient building standards, improved early~~
~~warning systems, and long-term adaptation strategies across northern~~ simulation. When interpreted in the context of established wind–damage relationships, these changes imply substantially enhanced potential for wind-related impacts.

Overall, the results demonstrate that thermodynamic warming alone can significantly amplify windstorm exposure, highlighting the importance of considering compound wind characteristics, when assessing future wind hazards and their impacts in Northern Europe.

1 Introduction

High wind speeds related to ~~the development of intensive~~ intense extratropical low pressure systems ~~,~~ represent a significant socioeconomic and environmental hazard (**?**). These intense weather events ~~cause extensive damage to natural and managed systems~~ result in substantial impacts on both natural and built environments, with the most immediate ~~impact for humans being structural destruction due to~~ consequences for human systems arising from structural damage caused by high sustained wind speeds and, ~~more critically~~ in particular, severe gusts (**?**). The forces resulting from the passage of such low-pressure systems can be very destructive (**?**), e.g. tearing roofs from buildings, uproot trees, and bring down power lines, resulting in widespread infrastructure disruptions. Transportation networks are particularly vulnerable, with bridge closures, flight cancellations, and railway disruptions leading to substantial economic consequences (**?**). Additionally, storms are often accompanied by storm surges, which amplify the overall damage to the coastal regions (**??**).

~~According to **?**,~~ Extreme wind events are inherently destructive because the force exerted on structures increases sharply with wind speed. Physically, the wind's kinetic energy scales with the square of its velocity, meaning that a doubling of wind speed quadruples the energy acting on buildings (**?**). In reality, the relationship between wind intensity and damage is often even steeper: Empirical studies show that economic losses tend to rise with the cube to fifth power of wind speed (**??**). Engineering simulations of structural failure sometimes use exponents as high as 8–12 (**?**), reflecting how seemingly modest intensifications in wind can translate into disproportionately large socioeconomic impacts.

To manage these risks, structural design standards employ standardized reference wind values that define the nominal wind conditions a structure must be capable of withstanding. In Europe, these are set by **?**, which specifies that the basic wind speed ~~value, which should only be surpassed once in~~ represents the 10-minute mean wind speed measured at 10 m height over open terrain, expected to be exceeded on average only once every 50 years~~, in Denmark is set at 24 m/s across most regions, except within a marginal zone at the west coast of Jutland. In this zone, which includes areas within 25 km of the North Sea, the basic~~. More specifically in Denmark, the main focus of the present study, the reference wind speed is ~~27~~ 24 m/s ~~at the coast, gradually decreasing to 24~~ for most regions, increasing to 27 m/s ~~at the zone's inland boundary. Therefore, assessing whether current adopted wind speed design levels will be challenged in a warmer world is of considerable interest.~~ within approximately 25 km of the exposed west coast of Jutland facing the North Sea. Assessing whether these design thresholds remain adequate under

climate change, given potential shifts in the frequency and intensity of extreme wind events, therefore represents a key question for future structural and risk assessments.

~~This study focuses on one of the most powerful storms recorded in Denmark: Storm Anatol, which struck on 3 December, 1999 (?). Anatol is classified as a storm based on widespread sustained wind speeds exceeding 24.5 m/s,~~ The development and intensification of extratropical storms are primarily governed by baroclinic instability, a ~~commonly used threshold for defining storm events. Anatol remains among the strongest storms measured by anemometers in Denmark[1], and its impact was profound. Although storms of this magnitude are relatively rare, their effects on society underscore the need for further investigation.~~ process driven by the convection of available potential energy arising from horizontal temperature gradients into kinetic energy (???). Stronger temperature contrasts within the troposphere enhance this instability, promoting stronger storms, which explains the predominance of storm systems during the winter months when meridional temperature gradients are strongest (??). Furthermore, latent heat release associated with the condensation of atmospheric moisture also contributes to an intensification of storm systems (?).

~~A key question arises: While no two storms events are identical, could a similar event become more intense in a warmer climate? Future climate projections, such as those assessed by the Intergovernmental Panel on Climate Change (IPCC), indicate that with rising global temperatures, changes in precipitation, and the intensification of several types of extreme weather events are also to be expected. While the thermodynamic effects of warming (??) and increased moisture (?) are well documented, significant uncertainty remains regarding the impact of climate change on extratropical~~ Because baroclinic instability and latent heating both depend on thermal gradients and moisture availability, future warming could substantially modify the energetic environment in which extratropical storms develop. Climate projections consistently show robust thermodynamic changes, particularly increased atmospheric moisture and altered meridional temperature gradients (???), yet the resulting effects on storm intensity and frequency remain uncertain. Some studies ~~, such as ?, suggest that while the intensity of individual storms may not increase significantly, there could be a rise~~ report an increase in the number of ~~storms exceeding 45 m/s in Northern Europe . Conversely, ? found no clear intensification of storms along the European coastline over the past century. There is currently no clear consensus regarding how wind patterns will evolve in a warmer climate. However, an increasing number of studies suggest a north–south contrast in future windstorm activity over Europe: northern regions, particularly around the North Sea and~~ very intense storms over Northern Europe (?), whereas others find no significant long-term trend (?). More recent analyses suggest a tri-polar pattern in projected windstorm activity, with enhanced intensity and frequency over the North Atlantic, the British Isles, ~~are projected to experience more frequent or intense wind events, while southern Europe may see either no significant change or a reduction in storm intensity (??)~~ and the North Sea region; a possible decrease across central and southern Europe; and mixed or slightly increasing tendencies toward northern Scandinavia (???).

~~This study examines the potential intensification of extreme cyclones in a warming climate. Building on the work of ? and ?, the 1999 Storm Anatol, also known in Denmark as "December-orkanen" is analysed. No storm in Denmark exceeding its intensity has occurred since, although the storm Allan (2013) (?) and the storm Erwin/Gudrun (2005) were close (?)~~ In light of

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[1] ~~The storm Allan - October 28, 2013 - reached a mean wind speed of 39.5 m/s, but surpassed Anatol in Gust reaching 53.5 m/s (?). This measurement was however made at a higher point at 17 m and therefore cannot be fully compared~~

these regional disparities and continuing uncertainty about how storm intensity responds to a changing climate, it is instructive to examine well-documented historical extremes that exemplify the upper end of Northern European storm behaviour.

The primary objective of this study is to assess whether a synoptic storm, like Anatol, could become more intense and disruptive in a warmer climate, while large-scale atmospheric conditions remain similar, by examining changes in mean wind speed and gust intensity and direction.

A storyline approach is employed (?), using a pseudo-global warming (PGW) method (?) to simulate Anatol under a future warming scenario. Event-based studies, such as this, are well suited for investigating how specific extreme events may respond to climate change (?). However, they pose certain challenges. Extreme storms are inherently unique, forming due to the precise alignment of multiple meteorological and climatological drivers (?). When modifying atmospheric conditions to reflect a warmer climate, there is a risk of altering the storm 'sfundamental dynamics, potentially reducing its extremity rather than amplifying it (see e.g. ?..

Importantly, this research does not assess whether the frequency of such events will increase in a future warmer climate, but rather investigates whether the intensity of an Anatol-like storms could be amplified under warmer conditions.

2 ~~The storm Anatol, viewed from a Danish perspective~~

~~On~~ This study focuses on Storm Anatol, one of the most powerful windstorms recorded in Denmark, which struck on 3 ~~December,~~ December 1999 , Storm Anatol impacted Denmark, southern Sweden and northern Germany, producing severe meteorological and hydrological consequences. Anatol developed rapidly over the eastern North Atlanticin early December 1999. Its formation was triggered by the interaction of two atmospheric disturbances, one at the surface moving northeast from Newfoundland and another in the upper atmosphere from Labrador. By the evening of 2 December, a closed surface low had formed west of Ireland, moving eastward along the southern edge of a cold upper-level trough centered over Iceland, see e.g., ?.

(?). Anatol intensified quickly in a zone of strong temperature contrasts, with warm air to the south and exceptionally cold air to the north. By early 3 December, its central pressure had dropped to around 990 hPa near the British Isles and continued falling, reaching a minimum of 952 hPa over eastern Jutland at 1800 GMT. It then moved across Denmark into Sweden and began weakening after crossing the Baltic Sea (????). Figure A1 illustrates the modeled trajectory of the storm, based on the simulations from HARMONIE-AROME.

The track of the modeled Storm Anatol, indicating the minimum pressure and location of the storm at 2-hourly intervals from 2 December 2200 UTC ending at 4 December 0600 UTC. Red dashed lines delineates the HARMONIE model domain. provides a valuable reference case for assessing whether current design-level wind speeds, as defined by ?, adequately represent the upper tail of observed extremes. The storm 's strongest winds occurred south of its center, affecting areas from the German and Danish North Sea coasts to Copenhagen and Poland. Denmark experienced widespread gale force winds and in the southern part of the country sustained winds reached storm force (>is classified based on widespread sustained wind speeds exceeding 24.5 m/s), with peak gusts exceeded hurricane force (>40 m/s) in exposed coastal areas from 1400 to 2200

GMT, peaking between 1600 and 1800 GMT with the passage of the cold front (e.g., ?) /s, the Beaufort wind scale definition of *Storm* (?), a commonly used threshold for defining storm events (?), and this criterion will be applied consistently throughout

125   the study, rather than the thresholds used locally in Denmark.

Anatol produced record-breaking wind speeds. During the event, 10-minute mean wind speeds exceeded 41.4 m/s, before the anemometer at Rømø failed, with gusts reaching 51.4 m/s onshore (?), categorizing it as a 100 year event (?). The offshore Mærsk Endeavour oil rig recorded a gust of 59.2 m/s at 40 m above mean sea level. Additional wind measurements included gusts of 41 m/s at Copenhagen Airport and 40 m/s on the island of Bornholm (?). The rapid intensification of Anatol has

130   attracted considerable scientific attention because it exemplifies the type of explosive cyclogenesis that can occur in the North Atlantic–European sector. Reanalyses and mesoscale modelling indicate that its deepening was partly driven by latent heat release within the warm conveyor belt (??), consistent with the recognized role of diabatic processes in intensifying baroclinic disturbances (?). This interplay between strong thermal gradients and moisture transport provides a physical analogue for the mechanisms expected to become more influential in a warmer and moister atmosphere.

135   The storm caused 800 injuries and 7 fatalities in Denmark, airports were closed, and transport greatly interrupted (?). Approximately 4 million m^3 of forest was damaged. Storm Anatol caused extensive damage to buildings, including the collapse of a large crane at the Odense shipyard. Widespread power outages occurred across Denmark, and the total economic loss was estimated at 1.7 billion EUR, which, adjusted for inflation, corresponds to approximately 2.8 billion EUR in 2024 (??). In Germany the storm losses reached 100 million EUR (?) and in Sweden 5 million m^3 of forest were damaged (?). Anatol

140   remains among the strongest windstorms ever measured by anemometers in Denmark, and its impact was profound. Both mean wind and gusts locally exceeded national design thresholds, causing widespread infrastructure damage and substantial economic losses. Although storms of comparable magnitude are estimated to occur only once per century in this region (?) , their severe societal consequences underscore the importance of revisiting how current design standards represent extreme wind risk with a view to climate change.

145   Given its intensity and extensive societal impact, Storm Anatol serves as a compelling case study for assessing the potential effects of a warmer climate on storm intensity.

Denmark was selected as the focus of this study because the storm had a particularly severe impact on the country, and detailed documentation of the storm severeness and resulting damages is readily available While no two storm events are identical, could a similar event become more intense and damaging in a warmer climate?

150   To address this question, the study employs the pseudo-global warming (PGW) approach (?) within a storyline framework (?). The PGW method modifies the thermodynamic state of the atmosphere, through a systematic adjustment of temperature and humidity, while preserving the original dynamical structure of the observed event. This simplified implementation follows approaches used in previous studies (???). This allows the investigation on how a known extreme system responds to a warmer and more moist climate, without altering the fundamental storm dynamics (??). The storyline approach provides a physically

155   coherent set of "what-if" scenarios, linking climate change to tangible, event based impacts (??). Building on the work of ? and detailed in ?, this study examines the impact of the potential intensification of an extreme storm in a warming climate.

2 ~~Theory~~

~~Extratropical cyclones develop and intensify primarily due to baroclinic instability, a process driven by the conversion of available potential energy (APE) into kinetic energy (?). This mechanism is fundamental to the growth of midlatitude weather~~
160 ~~systems and is well-documented in meteorological literature (e.g., ?). APE is generated from the temperature gradients in the troposphere, with stronger gradients providing more energy for cyclone growth. Baroclinic instability is a key mechanism for the development of such cyclones (?).~~

~~Additionally, latent heat release from phase changes in atmospheric moisture can contribute to cyclone intensification. The release of latent heat during condensation warms the atmosphere, reducing static stability and enhancing upward motion,~~
165 ~~which can further intensify cyclonic systems (?). Furthermore, studies have shown that the rapid intensification of Anatol was strongly influenced by latent heat release (??). This process has been identified as a significant factor in the explosive deepening of extratropical cyclones (?)~~While **?** focused primarily on the meteorological evolution and dynamical mechanisms governing Anatol's development in a warmer atmosphere, the present study addresses the consequences of these changes.

~~The availability of APE is proportional to temperature variations within the troposphere, which explains the increased~~
170 ~~frequency and intensity of extratropical cyclones during the winter months, when temperature gradients are typically more pronounced. Stronger temperature gradients enhance baroclinic instability, providing more energy for cyclone development and intensification (??).~~ Considering the impact of Analtol on Denmark, we introduce the Cumulative Wind Exposure Index (CWEI) to quantify the integrated spatial and temporal severity of wind exposure, assess the duration of wind threshold exceedances, and analyse directional changes in near-surface winds over land. These aspects provide a complementary perspective
175 on how thermodynamic perturbations may translate into enhanced wind-related impacts.

~~Since the early 1980s, reports have suggested an increasing trend in storm events over the North Atlantic region, although the available data covered only a short time frame (?). This trend raised concerns about a possible link to climate change (?). ? identified an increasing trend in storm activity over northern Europe and the North Atlantic, while noting a negative trend over southern Europe. Future climate projections indicate a rise in storm frequencyduring the winter months over the~~
180 ~~North Atlantic and Western Europe (?). However, these projections are highly dependent on the climate models used, with variations in the predicted magnitude and spatial distribution of storm activity (?). Some models project an increase in cyclonic activity over regions like the British Isles and Denmark, while others suggest decreases in different areas, highlighting the uncertainties inherent in such projections (?). Similarly, ? found that global warming is expected to reduce the frequency of extreme winds in the tropics while increasing their occurrence in the extratropics. This pattern appears to be strongly linked~~
185 ~~to the intensification and poleward shift of midlatitude storm tracks~~Rather than evaluating changes in storm frequency, this study isolates the thermodynamic influence of a warmer atmosphere on the intensity, structure, and surface wind impacts of an Anatol-like event under otherwise comparable large-scale conditions.

2 Methodology~~, model and Data~~

~~Storm~~

2.1 Harmonie model and data

Anatol has been the subject of extensive analysis in both meteorological literature and media reporting due to its severe impact in first and foremost Denmark but also more widely across Northern Europe (**??**). In the present study, the storm is re-evaluated using the HARMONIE-AROME limited-area numerical weather prediction (NWP) model to explore its sensitivity to varying temperature conditions. ~~A historical 1999 reference simulation (control run) is conducted, using conditions taken from ERA5 alongside four additional experiments in which the atmospheric temperature is systematically perturbed by +1° C, 2° C, +3° C, and −1° C. These perturbations are applied throughout the entire atmosphere in the initial and boundary conditions. These modifications aim to emulate plausible future warming scenarios as well as approximate preindustrial (PI) climatic conditions (?). The validation of the model data is described in ?.~~

2.2 ~~Harmonie Model and data~~

The simulations are carried out using the HARMONIE-AROME weather model (**?**) based on cycle 43h2.2~~.~~ ~~The utilised model setup has a horizontal~~, with a horizontal grid resolution of 2 km with 90 vertical levels between the surface and 10 hPa~~(~~, corresponding to approximately 25 km above sea level~~),~~, thereby capturing mesoscale atmospheric processes with high fidelity as evident from routinely operational applications across the Nordic countries and beyond. ~~A model setup similar to that used operationally by the United Weather Centres West (comprising Denmark, Iceland, the Netherlands, and Ireland) is adopted , featuring a broad domain extending into~~

A broad model domain extending into the North Atlantic is adopted to ensure a dynamically consistent representation of the large-scale flow influencing the storm evolution. The domain covers a large fraction of the North Atlantic ~~, see~~ Ocean, enabling the capturing of the development of Anatol from the initial upper level Rossby wave disturbance to grow to a matured storm when reaching Denmark as well as most of the decay on its path over the Baltic Sea. The model employs a rotated Lambert conformal grid covering the area from $28°$ W to $37°$ E and $44°$ N to $73°$ N, ensuring nearly uniform physical grid spacing across the domain. For a visual reference, the grid domain is shown in Appendix Figure A1. This ~~wide coverage enables extended~~ setup enables an extended and dynamically consistent simulation of the ~~cyclone~~ storm under PGW-modified conditions. ~~The model is run without data assimilation, as the event is primarily driven by large-scale upper-level atmospheric dynamics.~~

Initial ~~conditions~~ and lateral boundary ~~data are derived from the~~ conditions are provided by ERA5 reanalysis (**?**), ~~with boundary~~ and updates every 3 hours. ~~The initial forecast is started from an interpolated~~ Sea surface temperatures are likewise specified by ERA5 ~~analysis, while each subsequent run is started using the +6-hour forecast from the prior cycle to mitigate~~. All ERA5 data are horizontally and vertically interpolated to the HARMONIE-AROME model grid and vertical levels. To reduce model spin-up ~~issues.~~ effects, the simulations are initialized from ERA5 at the beginning of the experiment, while subsequent integrations are initialized from the preceding model state. Further details on the experimental setup are provided in **?**.

~~As detailed in **?**, each simulation consists of 11 forecast cycles, initiated every 6 hours over the period 01–03 December 1999, each providing a 24-hour forecast. Model output is saved at hourly intervals, except for wind speed, which is stored every 15 minutes to capture short-term variability and peak intensities.~~

The control simulation uses unmodified ERA5 temperatures, while the anomaly runs incorporate uniform perturbations throughout the model domain to the initial state and at the boundaries. To produce a temporally consistent time series of the storm's life-cycle, a mosaic is compiled using the model output from forecast hours +09 to +14 from each run. This method ensures continuous hourly coverage during the most dynamically active phase of the ~~cyclone.~~ storm.

Each simulation comprises 11 forecast cycles, initiated every 6 hours between 1 December 1999, 00 UTC and 3 December 1999, 12 UTC, each providing a 24-hour forecast. Model output is saved at hourly intervals, except for wind speed, which is archived every 15 minutes to capture short-term variability and peak gusts. The control simulation represents the historical 1999 event using unmodified ERA5 temperatures, while four additional experiments apply uniform temperature perturbations of -1 °C, +1 °C, +2 °C, and +3 °C throughout the atmosphere, as well as to the sea surface temperature. These modifications aim to emulate plausible future warming scenarios as well as an approximate preindustrial (PI) climatic condition (**?**). For the approach to have any validity the reference run must be documented to produce forecasts of the storm of high quality when compared to observations of the actual storm. Then the sensitivity simulations remain physically coherent and offer insights into how the same system might evolve under different climate conditions (**?**). In part due to the high resolution of the simulations, the reference run conducted with HARMONIE-AROME compares very well with observations, in particular sustained wind speeds and gusts are simulated realistically particularly over Denmark, the main focus of this study, as demonstrated in **?**.

Further details on the adopted HARMONIE-AROME model setup~~and physics~~, its physics parametrisation and general performance can be found in **?** and **?**.

2.2 Pseudo-global warming and story-line approach

The ~~Pseudo-global warming approach is a widely used method for assessing the potential impact of climate change on extreme meteorological events. The technique involves modifying the thermodynamic state of the atmosphere while preserving the original dynamical weather setup. Specifically, this is done by uniformly adjusting air temperature at all levels and then recalculating specific humidity~~ PGW framework is applied to investigate how a meteorological system would respond to systematically altered thermodynamic conditions. In the adopted approach, the temperature field in the initial and boundary conditions is uniformly modified, and specific humidity is recalculated to maintain the original relative humidity~~, thus emulating a warmer and moister climate (?)~~. The adjustment ensures that relative humidity remains constant, leading to higher specific humidity with increasing temperature according to the Clausius–Clapeyron relation (see **?**, Suppl. Info).

~~This approach allows retaining the essential structure of the meteorological phenomenon while examining how it responds to systematic climate shifts. Here, temperature modifications of~~ To portray the sensitivity to a warming climate, only uniform modifications were considered. It has previously been found (e.g. **?**) that applying climate changes found from climate simulations tend to increase overall atmospheric stability and thereby reduce the inherent extremity of the original meteorological conditions, which are a prerequisite for intense synoptic development.

255 The simulations with −1° C, +1°+1° C, +2° C, and +3° are applied to the Initial Conditions and Lateral Boundary Conditions, as well as to skin temperature and sea surface temperature that are used by the weather model. The procedure for adjusting specific humidity is detailed in ?. These modified simulations are directly compared with an unmodified reference +3° C perturbations are compared directly with the unmodified control run, providing a physically controlled basis for analysing changes evaluating changes in storm intensity and structure.

260 The −1° C simulation approximates a pre-industrial climate state (?), while the +1° C to +3° C runs represent plausible future warming scenarios. These enable us to evaluate how Anatol's wind intensity and related impacts might change under increasing global temperatures, within a storyline framework (?).

The use of spatially and vertically uniform perturbations is informed by prior studies (??), which showed that PGW scenarios derived from general circulation model (GCM) outputs can unintentionally alter the dynamics that originally produced the 265 extreme event. Such alterations can dampen the intensity of the simulated extremes, thereby reducing the realism of the modified future scenarios (?). In addition sensitivity tests (not shown here) were conducted on vertical temperature lapse rates and the overall large-scale north-south temperature gradient . These

Additionally, two sensitivity simulations were conducted; (1) to test the vertical lapse rate dependency, (2) to test the importance of the meridional temperature gradients. For the first experiment, the lower troposphere lapse rates were altered, 270 with a maximum change at the surface, and a linearly decreasing modification with height until 700 hPa, from where the vertical structure remained unchanged. For the second experiment, the same vertical lapse rates modification was made, however the magnitude at the surface, and hence the following vertical lapse rate change, were made latitude dependent, symmetrical around 55°N, following the approximate storm track.

For both sensitivity experiments, only minor changes to the cyclone development were identified, with similar deepening 275 rates and general wind extents. Furthermore, the enhanced wind drivers discussed, showed no sign of changes, in contrast to the main experiments (see ?). Motivated by the dominating cyclogenesis drivers; meridional temperature gradient and vertical static stability, these experiments further confirmed that overly smoothed thermodynamic changes may reduce the storm system's dynamic response, again consistent with findings by ? and ?.

The storyline approach is particularly valuable for this type of analysis. Rather than focusing on probabilistic outcomes, it 280 provides a set of physically self-consistent "what-if" scenarios for a known extreme event. By comparing modified simulations with the reference run, addressing whether increased or decreased wind intensity is plausible and identify the mechanisms responsible can be explored. This method helps isolate primary and secondary processes driving the storm's behavior—processes that might otherwise be overlooked due to the complex, multiscale nature of mid-latitude cyclones (?).

Importantly, the scientific validity of this method depends on the quality of the reference run. If the reference accurately 285 replicates the observed event, the sensitivity simulations remain physically coherent and offer insights into how the same system might evolve under different climate conditions (?). As demonstrated in ?, in part due to the high resolution of the simulations. The reference run conducted with HARMONIE-AROME compares very well with observation, in particular sustained wind speeds and gusts are depicted realistically.

2.3 Cumulative wind exposure index ~~(CWEI)~~

To assess the severity of a storm ~~,~~ it is essential to consider not only the peak wind speed but also the duration of high wind conditions, as prolonged exposure can significantly affect the structural integrity of materials (**??**). In addition, the total economic loss associated with a storm is closely linked to the spatial extent of the impacted area (**?**). To capture these combined effects, a ~~simple~~ novel index is introduced that integrates wind intensity, duration, and spatial coverage ~~.~~

~~In this study, storm severity is quantified using~~ ; a Cumulative wind exposure index (CWEI), which accounts for both the spatial extent and the duration of wind speeds exceeding a chosen damage threshold. The CWEI is defined as the cumulative sum of grid points and the time steps where wind speeds exceed a predefined ~~limit, normalized by that~~ threshold:

$$CWEI = \sum_{t=1}^{T} \sum_{(x,y)} 1(W_{t,x,y} > W_{thresh}) \tag{1}$$

$W_{(t,x,y)}$ denotes the mean wind speed at time t at the location (x,y), W_{thresh} is a predefined threshold, $1(\cdot)$ is the indicator function, equal to 1 if condition is true otherwise 0.

While ~~a number of~~ several storm severity indices ~~have been developed~~ exist (e.g., **?**, **?**), ~~many are designed for climatological analysis and~~ these mostly rely on percentile-based thresholds ~~, such as the 98th percentile of wind speeds. These are useful for statistical consistency across time and space, especially when comparing model output or reanalysis across long periods.~~ that are more appropriate for climatological analysis. For engineering and economic applications, absolute thresholds tied to structural damage or insurance claims are more relevant.

~~However, percentile-based thresholds may be less intuitive from an economic or engineering perspective, where losses and structural damage are tied to fixed, absolute wind speeds. Insurance claims , for instance, are typically triggered when gusts exceed regionally defined thresholds—not percentiles.~~ In much of Europe, ~~24.5~~ sustained wind speeds around 24–25 m/s ~~is used as a benchmark for storm events relevant to loss modeling and payout eligibility.~~

~~Additionally, from a constructional perspective, structural standards such as the **?** specify characteristic wind actions based on expected maximum gusts, not relative thresholds. By aligning the CWEI formulation with such fixed values, the metric offers a more practically grounded assessment~~ are typically regarded as indicative of severe storm conditions. The CWEI integrates wind magnitude, spatial extent, and duration relative to such a threshold, providing a physically based and practically grounded measure of storm severity ~~—especially for applications related to infrastructure risk, adaptation planning, and insurance exposure.~~

~~The CWEI should therefore not be seen as a replacement for existing indices but rather as a complementary tool that integrates wind magnitude, spatial impact, and duration into a single, transparent metric tied to real-world damage criteria. Its simplicity and adaptability make it especially suited for single-event sensitivity studies such as this one~~. The threshold itself is

not critical to the index formulation; it can be adjusted to reflect local design standards or specific analytical purposes. CWEI thereby complements existing metrics and is particularly suitable for event-based sensitivity analyses, as applied in this study.

2.4 ~~Storm damages~~

~~Extreme wind events are inherently destructive due to the physical relationship between wind speed and the force exerted on structures. The kinetic energy of the wind, which scales with the square of the velocity (v^2), provides a basic physical foundation for understanding storm impacts (**?**). However, when assessing actual damage and economic losses, especially those reflected in insurance data, the relationship between wind speed and financial loss is often found to be steeper than v^2.~~

~~Empirical studies have shown that insured losses frequently scale with higher powers of wind speed. For example, a cubic relationship (v^3) has been used in several risk assessment models (**?**), while others support a quartic or quintic dependency (v^4–v^5), especially for modelling storm losses over Europe and North America where building exposure is high (**?**). These mid-range exponents are commonly applied in insurance and reinsurance models aiming to estimate aggregate losses over large regions with varying building codes and vulnerability profiles.~~

~~In contrast, higher-order exponents such as v^8 to v^{12} have been used in contexts where the focus is on local or asset-specific damage, particularly in engineering-focused studies that simulate wind loading on structures or consider total failure scenarios (**?**). These exponents reflect the compounding effects of high winds on exposed infrastructure, where small increases in wind speed can disproportionately escalate the damage.~~

~~The choice of exponent is therefore context-dependent: lower exponents (v^2–v^3) capture general physical forces, moderate exponents (v^4–v^5) are often applied in large-scale insurance risk models, and higher exponents (v^8–v^{12}) are reserved for detailed local assessments or engineering design considerations.~~

3 The storm Anatol viewed from a Danish perspective

The Storm Anatol impacted Denmark, southern Sweden and northern Germany on 3 December 1999. Anatol developed rapidly over the eastern North Atlantic in early December 1999. Its formation was triggered by the interaction of two atmospheric disturbances, a surface baroclinic wave tracking north-east from Newfoundland and an upper-tropospheric shortwave trough descending from the Labrador Sea. Their interaction enhanced baroclinic instability and initiated rapid cyclogenesis. By the evening of 2 December, a closed surface low had formed west of Ireland, moving eastward along the southern edge of a cold upper-level trough centred over Iceland, (e.g. **?**).

Anatol intensified quickly in a zone of strong temperature contrasts, with warm air to the south and exceptionally cold air to the north. By early 3 December, its central pressure had dropped to around 990 hPa near the British Isles and continued falling, reaching a minimum of 952 hPa over eastern Jutland at 1800 UTC. It then moved across Denmark into Sweden and began weakening after crossing the Baltic Sea (**????**). The modelled trajectory can be found in Appendix Figure A1.

The storm's strongest winds occurred south of its centre, affecting areas from the German and Danish North Sea coasts to Copenhagen. Denmark experienced widespread gale force winds and in the southern part of the country sustained winds

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reached storm force (>24.5 m/s), with peak gusts exceeded hurricane force (>40 m/s) in most of the southern part of Denmark from 1400 to 2200 UTC, peaking between 1600 and 1800 UTC with the passage of the back-bent front (e.g. **?**)

355   Anatol produced record-breaking wind speeds. During the event, 10-minute mean wind speeds exceeded 41.4 m/s, before the anemometer at Rømø failed, with gusts reaching 51.4 m/s onshore (**?**), categorizing it as a 100 year event (**?**). The offshore Mærsk Endeavour oil rig recorded a gust of 59.2 m/s at 40 m above mean sea level. Additional wind measurements included gusts of 41 m/s at Copenhagen Airport and 40 m/s on the island of Bornholm (**?**).

    The storm caused about 800 injuries and 7 fatalities in Denmark, airports were closed, and transport greatly interrupted (**?**)

360   . Approximately 4 million m^3 of forest was damaged and extensive damage to buildings, including the collapse of a large crane at the Odense shipyard were seen. Widespread power outages occurred across Denmark, and the total economic loss was estimated at 1.7 billion EUR, which, adjusted for inflation, corresponds to approximately 2.8 billion EUR in 2024 (**??**). In northern Germany the storm losses reached 100 million EUR (**?**) and in Sweden 5 million m^3 of forest were damaged (**?**).

4 Results
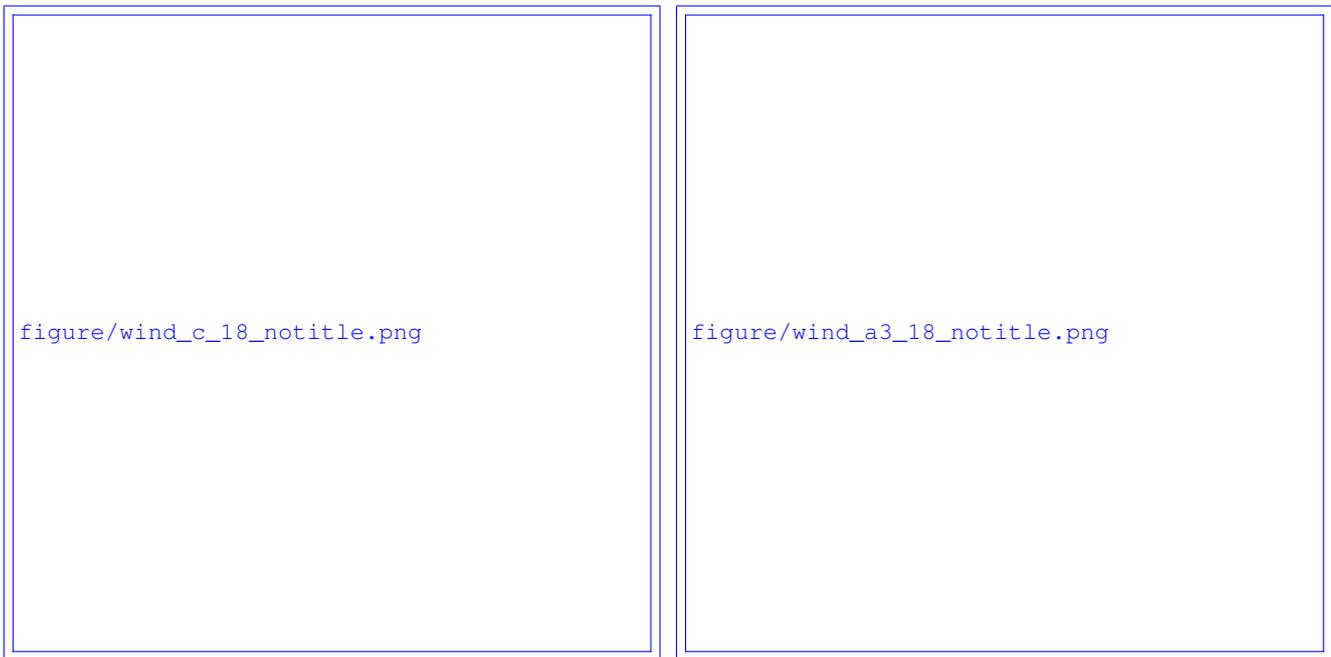
(a) Storm at UTC 18, control run

(b) Storm at UTC 18, +3° C Run

Figure 1. The storm intensity, shown by colour, and low pressure system, shown by the black contour-lines, at 3 December, 1800 UTC, ~~when the storm made landfall~~ for each of the different model runs of the Control run and +3° C. The plots for the other runs of −1° C, +1° C and +2° C are shown in appendix B.

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~~To assess the potential impact of a warmer counter-factual climate on extratropical cyclones, the storm Anatol was simulated under different temperature scenarios using the HARMONIE-AROME limited-area NWP model. This study primarily focuses~~ In order to emphasize the role of warming, this study will primarily focus on the difference observed between the control run and the +3° C warming scenario.

In terms of intensity of the wind speed and structure, the storm event is well reproduced by the HARMONIE model, ~~Figure 1~~(Figure 1). This figure shows the modeled 10 m ~~mean~~ wind speed and ~~msl~~ mslp at 1800 UTC~~, just before the storm makes landfall~~. The spatial structure of the control run, ~~Figure 1a~~ (Figure 1a) and the +3° C model run, ~~Figure 1b~~ (Figure 1b) are broadly similar. However, the +3° C run displays visibly stronger wind speeds, indicated by the darker red shading. ~~Notably, the center of the low-pressure system shifts eastward with each degree of warming, but there is only an modest deepening of the central pressure from 954 hPa to 952 hPa. The modeled~~ Small differences in the exact storm location between the two simulations (?) limit the direct interpretability of a difference map. For completeness, however, the difference plot is included in Appendix B1 as a supplementary visual reference.

The other warming scenarios are shown in Appendix Figure B2 illustrating the pressure system and wind for all simulations, highlighting these shifts. The modelled winds from the control run are generally similar to, though slightly higher, than the in-situ measurements from the actual event, providing validation for the models output (see ?).

The development of the low-pressure system is pictured in figure 2. At 1800 UTC, corresponding to the onset of peak wind intensity over land, the low-pressure centre is slightly shifted eastward with increasing temperature. This is accompanied by only a modest deepening of the central pressure, from 954 hPa in the control run to 952 hPa in the +3° C simulation.

~~−1° C Ref +1° C +2° C +3° C~~

~~Max mean velocity 44.5 m/s 44.2 m/s 45.9 m/s 45.6 m/s 46.7 m/sMax gust velocity 58.9 m/s 60.1 m/s 62.2 m/s 60.2 m/s 62.5 m/s~~
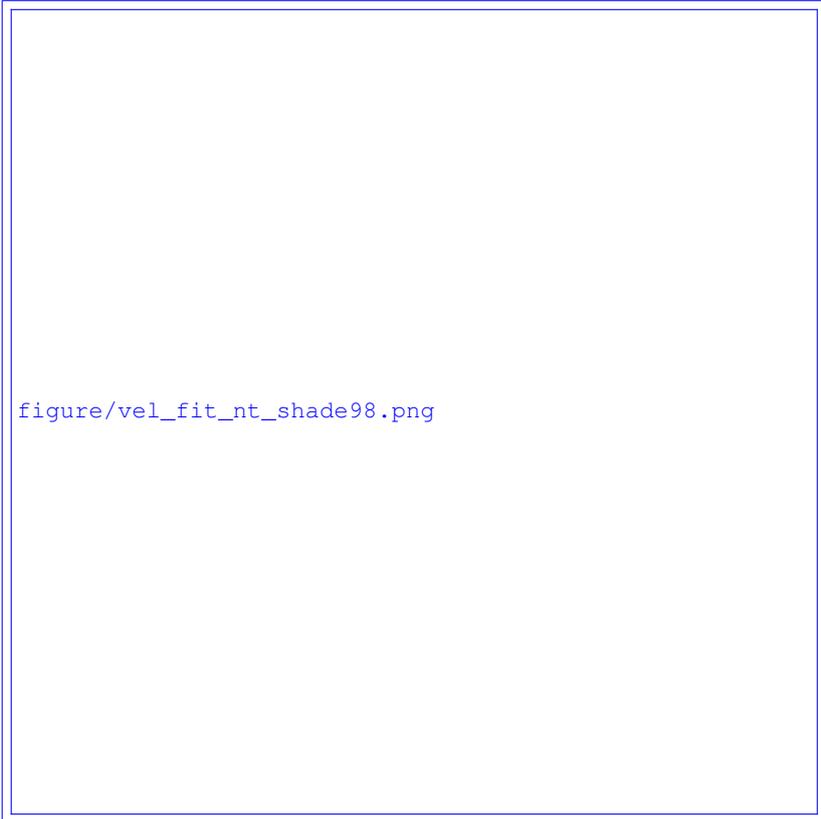
~~Table ??~~ The Figure 3 presents the maximum ~~wind speeds from within the entire model domain~~10 m wind speed, for both mean and gust wind components~~. The overall intensity of the storm increases by roughly 0.6~~, obtained over the entire simulated period and across the full model domain. The simulations indicate a tendency for higher maximum mean wind speeds and gusts under warmer temperature conditions. Max wind speed increases by approximately 0.6 m/s per ~~degree of warming for mean wind speed, with a moderately strong linear relationship~~° C of warming (R² = 0.78)~~. For gust, the increase is about 0.7~~, while gusts show a weaker increase of about 0.7 m/s per ~~1°C of warming, though the fit is weaker~~° C (R² = 0.57). The 98% fractile of the storm only shows a small increase of 0.2 m/s per degree of warming (R² = ~~0.58). These trends, illustrated in Figure 3, highlighting a potential amplifying effect of a warmer climate on storm events.~~0.37). Although the relationship is not strictly monotonic across all perturbations, these results suggest a modest strengthening of near-surface peak winds in warmer scenarios.

This increase in maximum wind speed results in an increase in wind pressure on constructions in terms of kinetic energy with ~~11.7~~12 % and a power increase of 18 %. The empirical large scale insurance risk model increases in the range of ~~24.7 % − 31.8 %~~25 % − 32% and the higher detailed assessment increases by ~~55.6 % − 94.1~~56 % − 94 %. These values are calculated based

Figure 2. ~~Overview of~~ The low pressure system for the ~~maximum mean wind velocity~~ control run (black line), PI run (green dashed line) and ~~wind gust over land reached by each scenario~~ +3° C run (violet dashed line) at different time. The colourbar follow the control run.

Figure 3. ~~Increase~~ Overview of ~~absolute~~ the maximum mean wind speed ~~pr~~ and wind gust over Denmark for each scenario during the storm period. The figure also illustrates the increase in maximum wind speed per degree of warming for both mean wind and gust.

on the various ~~methods described above~~exponents linked to calculating damages to constructions in terms of inflicted force (v^2), risk assessment/insurance $(v^3 - v^5)$ and total failure $(v^8 - v^{12})$.

Figure ~~C1~~ 4 illustrates the duration of land area affected by wind speeds equal to or exceeding storm-force wind speed (e.g. 24.5 m/s), emphasizing the substantial impact of Anatol on southern Denmark ~~.~~ and the northern most parts of Germany. The figure depicts the full spatial footprint of the storm. As the primary focus of this study is Denmark, arguably the region most strongly impacted by the highest wind speeds, corresponding results for Denmark alone are presented in the appendix Figure C1. In the control run (Figure ~~C1a~~4a) storm-force winds persisted for up to eight hours in the western part of ~~the country for up to eight hours~~Denmark and northern Germany, where mostly constrained to within a few kilometres from the coast as far south as at the Elbe river mouth. In contrast, the $+3°$ C scenario (Figure ~~C1b~~4b), the storm remained active for more than nine hours in some areas. As shown, the storm with sustained winds exceeding 24.5 m/s was largely concentrated over Denmark, with only limited impacts along the northwestern coastline of Germany and the southernmost parts of Sweden. Table 1 shows the areal percentage of Denmark subjected to storm in various hours.

~~Areas that experience variations in the duration of storm.~~

(a) ~~Storm affected land for the control~~ Control run

(b) ~~Storm affected land for the~~ Run $+3°$ C~~model run~~

(c) ~~Time of which Danish land affected by wind above 24.5 m/s for the control run and the~~ Difference between $+3°$ ~~C. The colourbar indicates the time each grid point experiences storm.~~ and Control run

Figure 4. The footprint of the storm with wind above 24.5 m/s for the control run and the $+3°$ C. The colourbar indicates the time each grid point experiences storm. Figure 4c shows the difference between the 2 model runs.

~~In figure C1c the time lapse for land areas experiencing either an increase or decrease in the period exceeding storm force over the area is presented~~ In figure 4c the difference in the duration during which storm force conditions are exceeded over land is shown. The northern part of the storm-area seems to experience a decrease in the storm-period from the control run to the $+3°C$ run, whereas the middle and southern part of the area affected experiences an increase in the storm period of up to ~~3 hours. 10~~ 6 hours. Overall 13 % of the affected area experiences an increase ~~compared to 4.2~~ in storm duration, compared to 8 % ~~that will experience~~ showing a decrease. ~~This is likely attributable to a slight change in the storm track, with the core wind field shifted slightly southward, suggesting that the reduction in duration may be an artifact of individual model realizations.~~

For Denmark the corresponding numbers are 10% for an increase and 4% for a decrease (Figure C1c). Furthermore, the percentage of land area in Denmark affected by wind speeds exceeding 24.5 m/s increases from 18.4 % in the control run to 21.5 % in the $+3°$ C scenario, a difference of approximately 1500 km^2, as described in Table 1. Also shown in the table are the CWEI values for each scenario at ~~particular~~ the wind speed thresholds ~~.~~ of 24.5 m/s, calculated for the period 1400 to 0000 UTC with the model resolution of 2 km. 10723 grid points were included in the calculation. Similarly, for gusts exceeding 40 m/s[1], the impacted area rises from 29.5 % in the control run to 32.5 % in the $+3°$ C scenario, shown in appendix D1. The full range of coverage percentages for different thresholds (from 15 m/s to 24.5 m/s) is provided in the appendix, Table E1.

Table 1. Overview of the percentage of ~~land~~ Denmark affected by wind speed above 24.5 m/s at different durations, the total percentage of ~~land~~ Denmark that experienced storm and CWEI. An extended version is presented in appendix table E1, displaying the results for various thresholds.

	$-1°$ C	Ref	$+1°$ C	$+2°$ C	$+3°$ C
1 Hour	~~5.84~~ 5.8 %	~~5.69~~ 5.7 %	~~6.75~~ 6.8 %	~~6.66~~ 6.7 %	~~6.38~~ 6.4 %
2 Hours	~~3.52~~ 3.5 %	~~3.58~~ 3.6 %	~~4.47~~ 4.5 %	~~5.01~~ 5.0 %	~~4.26~~ 4.3 %
3 Hours	~~3.34~~ 3.3 %	~~3.40~~ 3.4 %	~~5.75~~ 5.8 %	~~4.74~~ 4.7 %	~~5.39~~ 5.4 %
4 Hours	~~4.32~~ 4.3 %	~~3.94~~ 3.9 %	~~3.05~~ 3.1 %	~~3.34~~ 3.3 %	~~3.34~~ 3.3 %
5 Hours	~~1.03~~ 1.0 %	~~0.98~~ 1.0 %	~~1.04~~ 1.0 %	~~1.12~~ 1.1 %	~~1.26~~ 1.3 %
6 Hours	~~0.51~~ 0.5 %	~~0.67~~ 0.7 %	~~0.51~~ 0.5 %	~~0.63~~ 0.6 %	~~0.61~~ 0.6 %
7 Hours	0.08 %	~~0.10~~ 0.1 %	~~0.18~~ 0.2 %	~~0.29~~ 0.3 %	~~0.24~~ 0.2 %
8 Hours	0.02 %	0.01 %	0.06 %	-	0.03 %
Total cover	~~18.65~~ 18.7 %	~~18.37~~ 18.4 %	~~21.81~~ 21.8 %	~~21.78~~ 21.8 %	~~21.51~~ 21.5 %
CWEI [grid point]	5256	5191	5895	5954	6035

Consequently, Anatol's CWEI increases by approximately 800 $km^2 h$ [2], per degree of warming for strong mean wind speeds (24.5 m/s), with a ~~strong~~ statistically significant linear fit (R^2=0.81) as shown in Figure 5.

~~Figure 6 illustrates the temporal development~~ The temporal evolution of the maximum wind speed ~~across~~ over Denmark for all five scenarios ~~.~~ during the period when the storm affects Danish land areas is shown in Figure 6.

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[1]40 m/s is often treated as a significant threshold for very dangerous situations

[2]Denmark's land area is represented by 10723 grid points in the model, with each grid point ~ 4 km^2.

Figure 5. Development of the CWEI for the 5 ~~modelled~~ modeled scenarios, showing the increase of Denmark effected over time.

Figure 6a shows that the realised maximum wind speed is generally higher in the warmer scenarios, all exceeding 45 m/s. The control run and the simulation ~~mimicing preindustrial (PI)~~ mimicking PI conditions exhibit similar behaviour. However, the PI run reaches a slightly higher peak wind speed. ~~This may be due to the $-1°$ C perturbation modifying pressure gradients, static stability, or baroclinicity in a way that locally enhances wind speeds, despite the overall reduction in thermal energy. The cooler perturbation may also have altered the storm's trajectory or internal structure, resulting in locally stronger winds than in the control run.~~

The timing of peak wind speeds varies among the scenarios. The $+2°$ C and $+3°$ C runs peak later, around 18–19 UTC, while the $+1°$ C, control, and $-1°$ C runs peak slightly earlier, at 17–18 UTC. Such variations might be expected, as even minor perturbations, including cooling, can influence storm intensity, position, and timing, particularly in mesoscale models where feedback processes are highly sensitive.

Figure 6b presents the proportion of the Danish land area affected by wind speeds exceeding 24.5 m/s. A clear trend emerges in which the affected area increases with warming. The control and PI runs show nearly identical behaviours, whereas all three warming scenarios exhibit a consistent increase in the affected land area throughout the storm's evolution. Notably, the maximum land area experiencing storm force winds occurs simultaneously for all three warming runs.
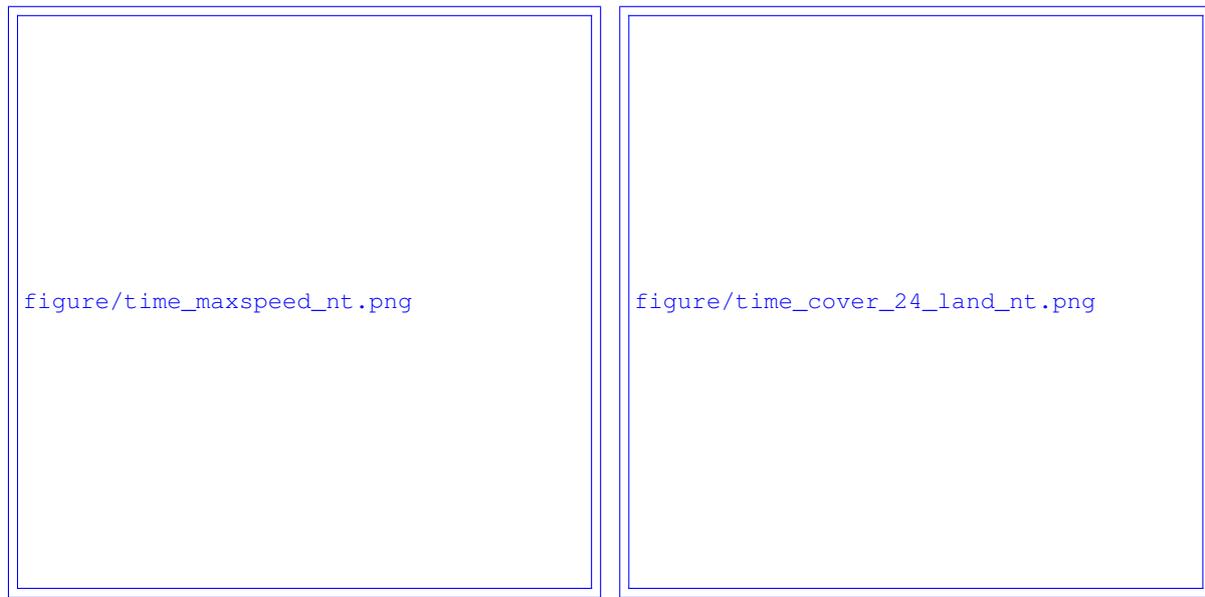
(a) Temporal variation of maximum mean wind velocity across the five scenarios.

(b) Distribution of land cover in percent across time slots for the five scenario simulations.
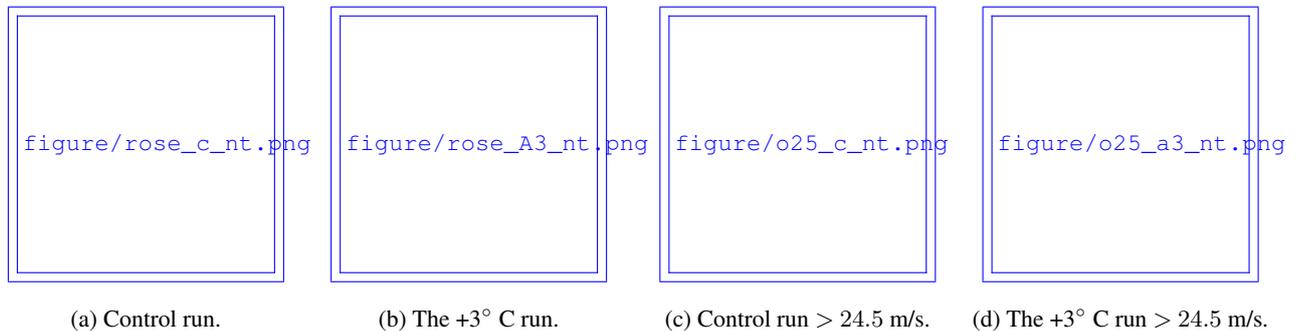
Figure 6. The time evolution of the maximum wind speed over land and the land affected by mean wind speed above 24.5 m/s.

In all scenarios, the wind directions consistently exhibits a Changes in near-surface wind direction were analysed to assess how a warmer and more humid atmosphere modifies not only wind intensity but also the spatial structure of the storm's footprint (Figure 7). In the warmer-climate simulations (Figure 7b and 7d), the large-scale near-surface wind field exhibits a modest but coherent clockwise rotation over much of Denmark and the adjacent North Sea. This behaviour is consistent with a slight displacement of the cyclone track and an eastward shift of the maximum pressure gradient, leading to enhanced westerly to south-westerly direction. The highest wind velocities tend to be more south-westerly flow over Jutland. As a result, strong winds penetrate further inland compared to the reference simulation.

Directional changes are more pronounced for the most intense winds (Figure 7c and 7d)compared to the overall wind field(Figure 7a and 7b). Notably, wind direction—when combined with coastal orientation and the layout of infrastructure—can influence vulnerability. In the warming experiments, the strongest near-surface winds shift toward more southerly and south-westerly sectors, particularly along the west coast of Denmark and in inner Danish waters. This reorientation focuses the highest wind speeds along coastal regions that are already highly exposed to storm surge and wave forcing, thereby increasing the potential for compound hazards. From an impact perspective, such directional shifts are particularly relevant, as they modify which coastlines, infrastructure corridors, and population centres are most exposed to damaging winds.

Overall, the combination of a slightly altered storm trajectory, modified pressure-gradient orientation, and enhanced thermal gradients aloft contributes to a moderately broader and directionally altered wind field. These changes extend both the duration

460 and the geographic extent of damaging winds and help explain the increases in cumulative wind exposure quantified by the CWEI. Thus, wind-directional changes provide an additional mechanism, beyond peak wind intensification, through which a warmer atmosphere amplifies the potential impacts of an Anatol-like storm.

figure/rose_c_nt.png	figure/rose_A3_nt.png	figure/o25_c_nt.png	figure/o25_a3_nt.png
(a) Control run.	(b) The +3° C run.	(c) Control run > 24.5 m/s.	(d) The +3° C run > 24.5 m/s.

Figure 7. Windrose displaying the wind direction for the two scenarios for all mean wind velocity and mean wind velocity above 24.5 m/s respectively. The data ~~used is for~~ show the maximum values over land for the period 3–4 December, 1400–0100 UTC, corresponding to the time of peak storm intensity.

5 Discussion

The simulation of Storm Anatol under varying temperature scenarios reveals ~~a clear~~ an intensification of the event with
465 warming. Across all scenarios, increases in both mean wind speeds and gusts ~~were identified~~are supported by the simulations, alongside an expansion in the spatial footprint of ~~storm-force winds and a~~ winds exceeding storm force and a local lengthening of the storm's duration. These changes are all associated with enhanced potential for infrastructural damage and societal disruption, emphasizing the importance of understanding how extratropical ~~cyclones~~ storms may evolve in a warming climate.

The trend of approximately 0.6 m/s per ~~1°C~~ degree of warming identified in this study is broadly consistent with the findings
470 of **?**~~of~~, who reported 1 m/s ~~pr~~ per 2 K in their simulation of the historical storm Ulysses. However, given the limited number of experiments considered here, the estimated trend carries substantial uncertainty, and the comparison should be interpreted qualitatively rather than quantitatively.

The ~~observed~~ simulated increase in the land area affected by storm-force winds is ~~consistent with previous findings. ?
found that~~qualitatively consistent with broader projections of enhanced storm exposure under future warming. Priestley and **?**
475 reported that, under high-emission scenarios such as ~~SSP5-8.5~~SSP5–8.5, the area ~~exposed to extreme storms could increase by
as much as 40 %~~ influenced by extreme extratropical cyclones could expand by up to 40% by the end of the century. While the ~~present study does not reach that magnitude , it confirms the general trend toward spatial expansion of storm impacts under warming conditions, even in a single-event simulation.~~ magnitude of change identified here is smaller, the directional agreement supports the broader understanding that a warmer atmosphere tends to extend the spatial footprint of damaging
480 winds.

20

It is important to emphasize, however, that the two studies differ fundamentally in scope and methodological design. **?** derived their estimates from coarser resolution multi-model climate simulations representing long-term statistical means, whereas the present analysis examines a single, dynamically consistent event using a non-hydrostatic high resolution weather model in a pseudo-global warming framework. The results should therefore be interpreted as a process-based illustration of how thermodynamic warming can modify storm structure and wind exposure, rather than as a probabilistic projection of future storm statistics. Nevertheless, the correspondence in qualitative trends lends confidence to the physical mechanisms identified here and demonstrates the value of detailed event-based analyses in complementing large-scale model assessments.

Event-based studies pose inherent challenges, as extreme storms are unique phenomena that arise from the precise alignment of multiple meteorological and climatological drivers (**?**). When modifying atmospheric conditions to represent a warmer climate, there is a risk of unintentionally altering the storm's fundamental dynamics, potentially reducing rather than amplifying its extremity (e.g. **?**). Moreover, regional NWP modelling introduces additional uncertainties related to initial conditions, boundary forcing, and physical parametrizations, all of which can influence the simulated storm structure and intensity. Consequently, thorough model validation is essential to ensure that the simulated sensitivities, such as those examined in this study, are physically meaningful.

The control simulation and the PI experiment exhibit broadly similar storm evolution and wind characteristics. However, the PI simulation attains a slightly higher local peak wind speed than the control run. This counterintuitive behaviour may reflect the sensitivity of wind maxima to small-scale dynamical adjustments rather than to thermodynamic forcing alone. In particular, the imposed cooling perturbation may have modified pressure gradients, static stability, or baroclinicity in a manner that locally enhanced near-surface winds, despite the overall reduction in available thermal energy. Small changes in storm trajectory or internal structure may likewise contribute to localized wind maxima that exceed those in the control simulation.

Beyond changes in maximum wind speeds, the CWEI provides a more integrative perspective on storm severity by combining wind intensity, duration, and spatial extent into a single metric. The consistent increase in CWEI with warming (approximately +800 km^2 h per °C; R^2 = 0.81) demonstrates that even modest thermodynamic perturbations lead to a substantial rise in total wind exposure. This indicates that the destructive potential of future storms cannot be captured by peak wind metrics alone but requires accounting for the cumulative loading and the area affected over time. The CWEI thus bridges meteorological change and impact relevance, offering a physically grounded yet application-oriented indicator that can be linked directly to damage functions, insurance risk models, or infrastructure design thresholds. Future studies could employ CWEI to compare storm severity across different synoptic types, assess climate-induced changes in regional exposure, or integrate with hydrodynamic models to estimate compound wind–surge hazards.

Notably, the relative increase in CWEI with warming is substantially larger than the corresponding increase in peak wind speed or gust magnitude. This indicates that the intensification signal is dominated not only by stronger winds, but by a combination of prolonged storm duration and an expansion of the area affected by high wind speeds. As a result, integrated exposure metrics such as the CWEI amplify warming-induced changes that may appear modest when considering maximum wind diagnostics alone.

Additional research is essential to build upon these findings. Simulations of other notable storms affecting Denmark and Northern Europe could assess the consistency of warming-induced intensification across different cases. Furthermore, integrating hydrodynamic models would provide valuable insights into how altered wind patterns may affect storm events, storm surges and coastal flooding risk~~—~~, an especially important consideration for low-lying and exposed regions. This study also does not address potential changes in storm frequency, which remain important but uncertain aspects of climate change impacts. These areas represent key directions for future investigation.

Finally, while much climate research has concentrated on changes in precipitation and flooding, less attention has been devoted to how climate change may affect the severity of windstorms in mid-latitude regions. Some global climate models suggest shifts in storm intensity, frequency, and storm track location under warming, though uncertainties persist~~—particularly regarding cyclone~~, particularly regarding storm genesis and path variability. ~~It is also worth noting that had Anatol occurred in the fall instead of winter, when sea surface and atmospheric temperatures are typically higher, the impacts may have been even more severe. Such seasonal considerations merit~~ Seasonal effects warrant further exploration in future ~~modeling efforts. Exploring the role of seasonal timing may offer additional insights~~modelling efforts. In particular, the timing of a storm within the annual cycle may be important, as higher autumn sea surface temperatures and increased atmospheric moisture could further amplify storm intensity and ~~related~~ associated impacts.

6 Conclusion

While it is not possible to attribute individual weather events to anthropogenic climate change in a strictly deterministic sense, advances in event attribution science, ~~notably~~ noticeable through efforts such as the World Weather Attribution (WWA) initiative (e.g., **?**), have demonstrated that the likelihood and severity of many extreme events, such as heatwaves, droughts, and

intense rainfall, have been significantly influenced by human-induced global warming. ~~. Extratropical cyclones~~ Extratropical storms such as Storm Anatol result from complex interactions involving atmospheric circulation patterns, boundary layer dynamics, and surface conditions. A warmer climate influences many of these background factors, thereby increasing the potential intensity and spatial footprint of such events (**?**).

This study used the HARMONIE-AROME limited-area model to examine how Storm Anatol might respond to warmer temperature scenarios. The simulations consistently show that increased temperatures lead to stronger winds, both in terms of mean wind and gust, longer storm durations, and larger areas affected by storm-force winds. Although the magnitudes of change are moderate, the signal is robust across all wind thresholds examined, suggesting a strong link between temperature and key storm severity metrics. Importantly, capturing these changes in storm structure and intensity requires the high spatial and temporal resolution provided by the NWP model, which exceeds that of typical climate model simulations and allows for more detailed representation of mesoscale dynamics and extreme wind events.

~~These findings are consistent with broader modeling literature indicating that intense extratropical storms are likely to become more intense and expansive under climate change. While the analysis is limited to a single storm, the results underscore the growing risks to public safety and critical infrastructure, even in regions where windstorms are already a familiar hazard.~~

~~This study contributes to the growing body of evidence that climate change is likely to exacerbate the impacts of extreme wind events. A more comprehensive understanding of these changes, both in terms of intensity and potential shifts in frequency or seasonal timing, is essential for informing adaptive strategies, improving early warning systems, and enhancing societal resilience to future storm extremes.~~

~~Ultimately, while this study cannot make probabilistic claims about future storm occurrences, it does contribute to the growing body of evidence that a warmer climate is likely to produce more impactful windstorms. Recognizing these patterns is crucial for informing adaptive planning and enhancing societal resilience to future extremes.~~ In addition to confirming a general intensification of near-surface winds under warming, the introduction of the CWEI provides a new means of quantifying storm destructiveness. By integrating wind intensity, duration, and spatial extent, CWEI captures the cumulative exposure that drives real-world damage and disruption. Its systematic increase with temperature underscores that even moderate atmospheric warming can lead to disproportionate growth in wind-related risk. This metric may serve as a valuable diagnostic for future event-based attribution studies and for translating physical wind changes into engineering and societal impact assessments.

Appendix A: DINI

The HARMONIE-AROME uses the DINI configuration shown in Figure A1. This covers the area of Iceland, Great Britain, most of Sweden and Norway and a great part of Europe. This domain is big enough to cover the entire development of Anatol from the initial upper level Rossby wave disturbance started to grow to the storm matured over Denmark and decayed on its path over the Baltic Sea and

Figure A1. The track of the modelled Storm Anatol, with indication of the minimum pressure and location of the storm at 2-hourly intervals from 2 December 2200 UTC ending at 4 December 0600 UTC. Red dashed lines delineate the HARMONIE model domain, which extend from 28 W - 37 E, 44 N - 73 N.

Appendix B: Wind

The difference between the control run and the 3° C warmer run are shown in Figure B1 for 1800 UTC.

Figure B1. The difference between the 3° C run and the reference run

Figure B2 shows the five scenarios of Storm Anatol at 18:00 ETC, corresponding to its landfall. While the overall structure of the storm remains similar across the scenarios, an intensification of wind speed is evident, as indicated by the increasingly darker shades of red.

585 **Appendix C: Storm in hours over Denmark**

Appendix D: Gust

The land area affected by gust exceeding 40 m/s is shown in Figure D1. Although the variations are less pronounced than those observed for the wind-affected area, there is still a general increase in gust exposure, as illustrated in Figure D2. Severe gusts are especially pronounced in the southernmost part of Denmark in the warmer climate run.

590 **Appendix E: CWEI**

The CWEI has been calculated for various thresholds as presented in Table E1 and illustrated in Figure E1
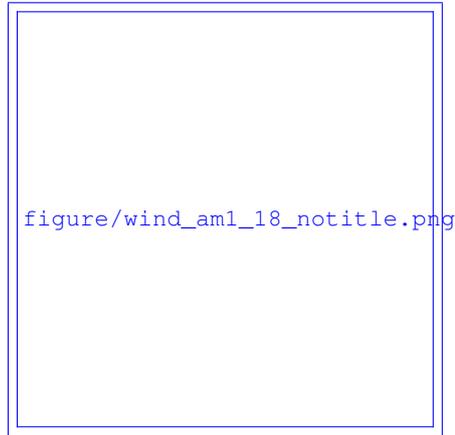
(a) Run -1° C
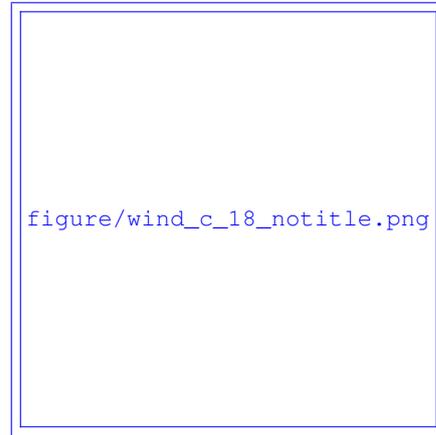
(b) Control run
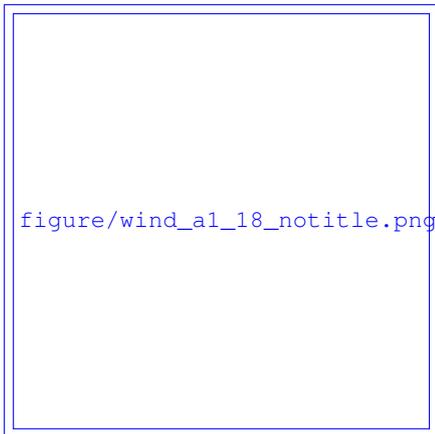
(c) Run $+1^\circ$ C
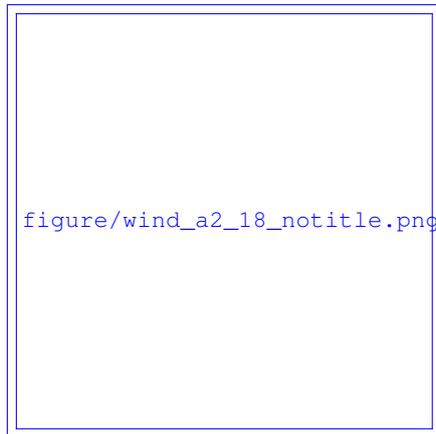
(d) Run $+2^\circ$ C
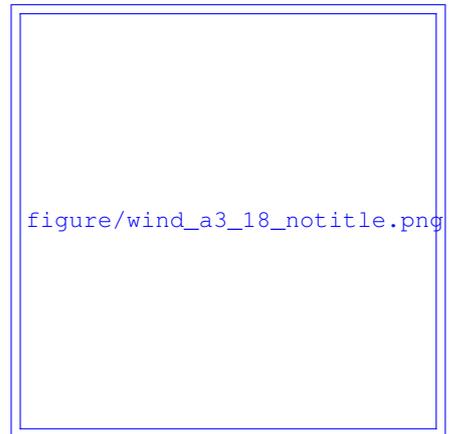
(e) Run $+3^\circ$ C

Figure B2. The storm intensity and low pressure system at 3 December 1800 UTC, when the storm made landfall for each of the different model runs of -1° C, Control run, $+1^\circ$ C, $+2^\circ$ C and $+3^\circ$ C.

(a) Control run

(b) Run $+3^\circ$ C

(c) Difference between $+3^\circ$ and Control run

Figure C1. Time of which Danish land affected by wind above 24.5 m/s for the control run and the $+3^\circ$ C. The colourbar indicates the time each grid point experiences storm. Figure C1c shows the difference between the 2 model runs.

(a) Land cover for the control run

(b) Land cover for the $+3^\circ$ C

Figure D1. Time of which land is affected by gust above 40 m/s for the control run and the $+3^\circ$ C. The colourbar indicates the time each grid point experiences gust above 40 m/s.

Figure D2. Area experiencing a variation in the duration of gust above $40m/s$

Table E1. The cover for the various scenarios and periods of wind at different thresholds including CWEI.

	15 m/s					17.2 m/s					18 m/s					20 m/s				
	−1° C	Ref	+1° C	+2° C	+3° C	−1° C	Ref	+1° C	+2° C	+3° C	−1° C	Ref	+1° C	+2° C	+3° C	−1° C	Ref	+1° C	+2° C	+3° C
1 Hour	5.71 %	6.34 %	8.77 %	7.08 %	7.52 %	9.92 %	9.45 %	9.93 %	9.55 %	9.19 %	10.23 %	9.62 %	8.64 %	9.76 %	7.87 %	9.50 %	8.84 %	7.09 %	9.50 %	6.79 %
2 Hours	14.38 %	13.59 %	12.17 %	11.42 %	10.62 %	10.61 %	9.86 %	7.16 %	8.73 %	7.65 %	8.26 %	7.93 %	6.06 %	7.56 %	6.85 %	6.70 %	6.35 %	6.21 %	7.57 %	6.63 %
3 Hours	7.46 %	7.36 %	5.35 %	7.87 %	7.68 %	4.19 %	4.35 %	3.82 %	4.26 %	5.31 %	4.19 %	4.39 %	4.61 %	5.13 %	5.70 %	6.57 %	7.07 %	7.57 %	7.95 %	8.67 %
4 Hours	4.72 %	4.41 %	4.31 %	5.15 %	5.42 %	5.75 %	5.09 %	5.01 %	6.22 %	6.46 %	8.90 %	7.66 %	7.60 %	7.68 %	8.36 %	8.77 %	9.22 %	9.69 %	10.09 %	10.64 %
5 Hours	5.52 %	5.27 %	5.07 %	4.89 %	4.77 %	14.64 %	13.98 %	14.18 %	12.17 %	10.66 %	15.29 %	15.36 %	15.54 %	13.25 %	12.14 %	11.89 %	11.08 %	10.22 %	9.58 %	8.72 %
6 Hours	6.17 %	5.55 %	5.48 %	5.46 %	5.33 %	9.16 %	9.25 %	9.69 %	9.07 %	10.97 %	6.89 %	7.25 %	7.33 %	9.01 %	9.81 %	1.85 %	2.02 %	2.06 %	2.56 %	2.46 %
7 Hours	6.12 %	5.99 %	6.63 %	6.78 %	7.06 %	5.91 %	6.53 %	6.12 %	8.63 %	7.27 %	3.40 %	3.47 %	3.44 %	4.91 %	4.14 %	1.26 %	1.24 %	1.39 %	1.18 %	1.35 %
8 Hours	6.54 %	7.05 %	8.48 %	6.59 %	7.52 %	2.56 %	2.82 %	3.22 %	3.32 %	3.16 %	1.49 %	1.59 %	1.74 %	1.87 %	1.81 %	0.71 %	0.80 %	0.83 %	1.05 %	0.89 %
9 Hours	6.28 %	6.56 %	6.65 %	7.26 %	6.94 %	1.59 %	1.32 %	1.75 %	1.73 %	1.86 %	1.02 %	0.92 %	1.30 %	0.94 %	1.11 %	0.69 %	0.55 %	0.68 %	0.72 %	0.75 %
10+ Hours	24.14 %	24.32 %	22.49 %	25.93 %	24.83 %	6.19 %	6.47 %	6.15 %	6.92 %	6.78 %	4.44 %	4.63 %	4.39 %	4.95 %	4.79 %	1.57 %	1.63 %	1.56 %	1.73 %	1.76 %
Cover	86.93 %	86.44 %	85.42 %	88.44 %	87.70 %	70.53 %	69.12 %	67.02 %	70.60 %	69.30 %	64.11 %	62.82 %	60.65 %	65.08 %	62.59 %	49.50 %	48.81 %	47.31 %	51.93 %	48.66 %
CWEI	56350	56402	55078	58343	57614	35175	35080	34769	37131	36552	29799	29646	29542	31618	30978	19583	19406	19302	20350	19881

	21 m/s					22 m/s					23 m/s					24.5 m/s				
	−1° C	Ref	+1° C	+2° C	+3° C	−1° C	Ref	+1° C	+2° C	+3° C	−1° C	Ref	+1° C	+2° C	+3° C	−1° C	Ref	+1° C	+2° C	+3° C
1 Hour	9.04 %	8.35 %	7.29 %	9.02 %	7.06 %	8.16 %	7.52 %	7.70 %	7.76 %	6.98 %	7.88 %	7.46 %	7.30 %	7.03 %	6.74 %	5.84 %	5.69 %	6.75 %	6.66 %	6.38 %
2 Hours	6.10 %	5.65 %	5.59 %	7.43 %	5.83 %	5.67 %	5.55 %	4.81 %	6.69 %	5.60 %	4.86 %	4.97 %	4.58 %	5.92 %	5.66 %	3.52 %	3.58 %	4.47 %	5.01 %	4.26 %
3 Hours	6.87 %	7.26 %	8.31 %	7.88 %	9.74 %	5.60 %	6.15 %	7.91 %	6.93 %	9.04 %	4.96 %	4.93 %	7.95 %	6.76 %	7.88 %	3.34 %	3.40 %	5.75 %	4.74 %	5.39 %
4 Hours	7.92 %	9.15 %	9.08 %	10.33 %	9.70 %	8.18 %	8.78 %	8.04 %	9.89 %	8.85 %	6.92 %	7.26 %	5.94 %	7.01 %	5.83 %	4.32 %	3.94 %	3.05 %	3.34 %	3.26 %
5 Hours	7.92 %	6.96 %	6.51 %	5.42 %	5.58 %	4.21 %	3.58 %	3.70 %	2.64 %	2.65 %	1.93 %	1.99 %	1.85 %	1.74 %	1.99 %	1.03 %	0.98 %	1.04 %	1.12 %	1.29 %
6 Hours	1.32 %	1.25 %	1.31 %	1.53 %	1.37 %	1.10 %	1.06 %	1.15 %	1.17 %	1.09 %	0.90 %	0.92 %	0.87 %	0.89 %	1.00 %	0.51 %	0.67 %	0.51 %	0.63 %	0.60 %
7 Hours	1.07 %	0.91 %	1.21 %	1.10 %	1.02 %	0.85 %	0.93 %	0.92 %	1.04 %	0.95 %	0.59 %	0.65 %	0.59 %	0.76 %	0.51 %	0.08 %	0.10 %	0.18 %	0.29 %	0.22 %
8 Hours	0.68 %	0.74 %	0.62 %	0.72 %	0.75 %	0.45 %	0.48 %	0.41 %	0.36 %	0.42 %	0.17 %	0.11 %	0.20 %	0.21 %	0.24 %	0.02 %	0.01 %	0.06 %	-	0.08 %
9 Hours	0.40 %	0.41 %	0.46 %	0.34 %	0.53 %	0.28 %	0.19 %	0.22 %	0.21 %	0.25 %	0.13 %	0.02 %	0.12 %	0.08 %	0.15 %	-	-	-	-	0.02 %
10+ Hours	0.69 %	0.76 %	0.68 %	0.90 %	0.90 %	0.16 %	0.21 %	0.27 %	0.30 %	0.44 %	0.02 %	0.02 %	0.01 %	0.03 %	0.11 %	-	-	-	-	-
Cover	42.01 %	41.43 %	41.07 %	44.67 %	42.47 %	34.65 %	34.43 %	35.14 %	36.98 %	36.28 %	28.35 %	28.34 %	29.39 %	30.43 %	30.11 %	18.65 %	18.37 %	21.81 %	21.78 %	21.51 %
CWEI	15368	15265	15308	15941	15881	11755	11747	11993	12377	12434	8759	8810	9096	9500	9444	5256	5191	5895	5954	6035

Figure E1. Development of the CWEI for the 5 model scenarios

Appendix F: Required Software and Dependencies

The following Python libraries and tools were used to access and process the data, along with the specific versions employed in this study:

cfgrib, version 0.9.10.4

ecCodes, version 1.5.0

xarray, version 2023.7.0

These constitute the minimum requirements necessary to handle the GRIB-formatted data used in the analysis. These libraries themselves have additional dependencies, which are typically resolved automatically when using standard installation tools.

. JKHØ: Formal analysis, Writing original draft, Investigation, conceptualization. JHC: Conceptualization, Review/ editing. RMKZ: Coding, Analysis, Review/editing. HV: Conceptualization, Review/editing. HF: HARMONIE-AROME simulations, Review/editing.